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Abstract

We installed two orthogonal Blum-Esnoult silica tiltmeters in an underground military facility close to the shore in Cherbourg (France). They have recorded the ocean tide and the associated oceanic loading effects from March 2004 to July 2005. The signal to noise ratio is such that, within a period range from a few minutes to a few days, the main nonlinear oceanic tides up to the M10 group could be observed. The modelling of the tidal tilt deformation has been carried out using oceanic models of the FES2004 family, with a stepwise refinement of the grid size. The comparison with recorded tilt time series shows spectacular improvement when refining the grid and also provides an independent mean to validate the oceanic models and the modelling process. We show that tiltmeters open new opportunities to explore loading of non linear tides on a larger spectrum than gravimeters and GPS do.

Keywords

Inclinometry, tilt, oceanic loading, FES2004, nonlinear tides

1. Introduction

The oceanic loading phenomenon involves the attraction and deformation of the Earth that are due to the varying weight of moving water masses in the oceans and seas, mainly the oceanic tides. These effects may be measured on the ground by several geodetic observables: classically gravity, land level displacement, (Llubes, 2001, Vey, 2002, Llubes, 2008), but also strain and stress can be used.

This paper is focused on to the tilt effects generated by tidal oceanic loading on the French coast (Cherbourg, Cotentin region). The tidal amplitude may reach there up to several meters.

While considering gravity variations in the vicinity of a sea with large tides, the proper loading contribution can reach about the third of the elastic earth tide variation (Llubes et al., 2004). Tilts are much more sensitive to the coastal loading because they result mainly from the flexure of the crust, which involves a sensitivity to shorter spatial scales than gravimetry does. Actually the tilt loading itself reaches at Cherbourg about three times the solid tide tilt effect. Precisely, two factors converge to generate a large amplitude to the loading tilt *locally*: 1) The decreasing rate of the tilt Green function as a function of the load distance is more rapid with respect to gravity: it behaves as $1/r^2$ instead of $1/r$. This feature leads to a sort of homothetic invariance scale (Rerolle et al., 2006) when integrating over an area which also depends on r^2; 2) Coastal areas are zones where the tidal amplitude is much greater than in the open ocean. Finally, these properties make the tiltmeters highly sensitive and suitable to study local loading phenomena.

Strictly speaking, tiltmeters record the variations of the gravity direction, more precisely the variations between the instantaneous geoid and the crust on which these instruments are settled. Both are affected by water loads. In practical terms, the only signal that can be reached is the difference between the geoid and the crust. It is not possible to refer tilts to a space or terrestrial reference frame because the accuracy that would be required to refer tilt data to this frame should be of the same order of magnitude than a tiltmeter resolution (at least), that is better than 10^{-9} at short time scale (a few seconds). Of course, it is only a practical limitation. Actually, the zero instrumental reference is just its initial state when beginning the record.

The geometrical and dynamical effects induced by the oceanic loads can be easily computed using the Green formalism, which degenerates in a simple convolutive formalism as long as the Earth is considered as spherically symmetric. Green functions describe the linear elastic Earth response to a local load in terms of vertical and horizontal displacements, stress, strain, gravity… Tilt Green functions can be found in Pagiatakis (1990). See also Boy et al. in this issue.

2. Experiment description and site corrections

2.1. Tiltmeters records

The tilmeters used in this experiment are very compact instruments historically designed by Blum (1962) (see also Saleh, 1991) and nowadays built by Marie-France Esnoult at IPGP. These instruments are made with silica glass and is built according to Zöllner's pendulum concept. Tiltmeters require a two-step calibration: the first one is electronic (the sensitivity of the displacement probe) and the second one is purely mechanistic (the amplification of a pendulum is $1/\sin(\alpha)$, α being the angle between the rotation axe and the vertical line). Scientific and historical background of this kind of probes may be found in Melchior (1983). Braitenberg et al. (1999) also provide a suitable summary of their functioning.

The tiltmeters used in this experiment can reach a resolution of about 10^{-9} rad. Actually the gain accuracy (calibration constant) is expected to be better than $4\ \%$ $(\text{at } 1\ \sigma)$. However, pendulums are affected by some "external" limitations. They are highly sensitive to very local environmental background variations: temperature, humidity of the supporting materials, and any kind of natural or induced deformation of the stand. For instance, assuming a 30 cm baseline tripod, a 1 micrometer stem vertical displacement would lead to a 3.10^{-6} rad tilt effect. Generally speaking, a noticeable drift is observed on that kind of instruments, which is rarely understood in details. This drift could also involve the creeping of the tiltmeter components themselves: it is worth mentioning that 10^{-9} rad variation over a 30 cm baseline is less than the elementary quartz crystal size. Hence, a suitable efficiency can only be reached thanks to exceptional settling conditions. In our experiment, two orthogonal pendulums have been installed in an unused part of a military underground installation owned by the French Marine, the “Souterrain du Roule”, at Cherbourg (Figure 1). A drift does actually exist on both tiltmeters directions (EW and NS). However, it only causes interferences within the long period variations (saying, more than a week), which can be eliminated by standard filtering methods to focus on the diurnal tidal band and its harmonics without spectral windowing artefacts.

2.2. Site effects

Site effects include both topographic and cavity effects. Both deform the local stress field and so they modify (magnify or reduce) the targeted tilt signal. Harrison (1976) was the first to provide a useful approach to deal with such undesirable effects. He clearly showed the major influence of the topography: in the core of a hill, the tilt could be changed by a large factor (from 0.25 to 10 outdoor in a talweg). An essential characteristic of site effects is the relative phase shift with respect to its theoretical value, which can reach as much as 40° (Lecolazet and Wittlinger, 1974).

The paper by King *et* al. mentions two issues to correct the site effects: first the practical problem of constructing and checking large three-dimensional models, and second the difficulties of obtaining the correct input data for the models. Nowadays, Finite Element Method (FEM) could be applied (see for instance Kroner *et al.* 2005). However, in our case it will not be very useful. These authors also remind us Itsueli *et al.* work (1975) in which the problem of the existence of surrounding fracture - that are not well mapped introduces additional difficulties. They proposed a method for removing the site effects without recourse to modelling by using a response method actually based on the seismic response or Raleigh waves. Neither of these methods can be used here. As stated by King et al (1976) the first method is valid only for sites distant from ocean loading and the second requires at least the vertical component which is not available in our case.

However two points must be emphasised to lower the site effects. Firstly, body forces are generally considered to study cavity effects, whereas the study of the crust flexure results from remote surface loads. Potential site effects are reduced to a shear effect alone. Here, the direct Newtonian attraction is lowered (water masses are more or less at the same altitude than the instrument) –however, the mass redistribution potential (and forces) cannot be neglected. Secondly, tiltmeters have been installed more or less in the middle of the tunnel (a symmetry axis), where the disturbing effect is supposed to vanish.

The solution we finally adopted consists in dropping potential site effect corrections, assuming it is less critical than in the frame of a body Earth Tide study. Finally, remembering that Lecolazet and Wittlinger (1974) associated a significant phase to cavity effect, we state that the undetectable phase difference between the observed and the modeled tidal tilt variations will be an a-posteriori justification of the reduced rule of site effect.

2.3. Atmospheric contribution on tilt.

The atmosphere contributes to the tilt as any other moving mass (Boy *et al*, this issue). Two deformation processes have to be modeled: direct attraction (modifying the equipotential), and the elastic deformation due to the additional pressure on the crust, which also implies mass redistribution and thus an effect on the geoid (Farrell, 1972). The formalism to compute the atmospheric contribution is similar to those used in the oceanic or continental (hydrological) loading problems, except that one should consider here that the station is inside the atmosphere shell. As in the hydrological case, tilts are only influenced by the spatial pressure gradient (Rerolle et al., 2006). It implies that the classical admittance method cannot be used in our case. Two methods can be used to correct the atmospheric pressure contribution. One would use a local barometer network, which would require a heavy installation structure because of the different spatial scales involved in the deformation. A test was carried out, but did not provide good results. Moreover, the pressure effect on that coastal border is complicated by the dynamic response of the ocean. The second method consists in using the atmospheric data as provided by meteorological models. Unfortunately, the sampling rate of these is too coarse, and does not allow to study phenomena below 12 hours. On a spectral point of view, pressure effects induce a rosy noise superimposed with periodic signals. If a good atmospheric pressure correction is expected to improve the S/N ratio, we suspect that it would be a real but light improvement in our spectral analysis. Finally, we dropped this correction since no data is available within the given frequency range.

Traditional Earth Tide (ET) studies have benefited from gravity observations, such as the GGP experiment (http://www.eas.slu.edu/GGP/ggphome.html). Most of the geodesists consider that the discrepancies between the observations and the models are very tiny. Actually, they are much smaller toward the inner continental stations where the influence of oceanic loadings is reduced. The agreement between the Love numbers used to compute Earth elastic tides and the GGP cryogenic gravimeter data is better than 1/100. This is indeed negligible when considering the factor calibration accuracy and one can assume that the modelled Earth tide elastic contribution is very accurate and can be subtracted from the raw data to leave only oceanic loading effects. However, the situation is not so simple if we remind the nature of the site effect. Here, an “exact tide” is subtracted from a signal where the tides could have been multiplicatively changed by the site magnification. Hence, the legitimacy to remove the elastic tide lies on the fact that i) it is smaller than the loading, ii) the site effect factor is not too far from 1 (due to the location of the probes near the center of the tunnels). The combination of these two “small” hypothesis let us hope that these approximations are not too dramatic, although it is not possible to estimate them with accuracy. Finally, we consider that the error associated with site effects is reduced due to (1) the position of the tiltmeters in the center of the tunnel and (2) the reduced amplitude of the Earth Tide by a factor 5 with respect to loading.

3. Signal processing and spectral analysis.

3.1 Basic spectral analysis

Tilts were initially sampled at 30 sec intervals. We applied high-pass filtering (to remove the drift) and resampling (with low-pass filtering to avoid aliasing). This finally restricts the bandwidth to the useful periods between 10minutes and 72 hours. Raw and filtered signals are plotted on Figure 2. The amplitude spectra of the filtered signals are plotted on Figure 3. We chose a spectral normalization which preserves the amplitude of the periodic signal rather than the density power spectrum. Hence, the tidal wave amplitudes can be directly read in microradians.

The spectra show several harmonics of the diurnal tidal waves. They are directly linked to the non-linear hydrodynamical waves in the English Channel (and do not result from any kind of non-linearity of the Earth elastic response). The most further way to model the observed amplitude requires to compute these non linear waves by using the most complete oceanic charts (involving hydrodynamic modelling plus data assimilation) and to combine them with the rheological response of the Earth (convolutive or more sophisticated). However, the difficulties of getting upper order waves lies in the mesh definition and restitution as seen by altimetric satellites, more exactly it depends on the trade-off between time and space sampling, both limited in practice (Cartwright and Ray, 1990). This becomes more and fussier as the order increases, since the higher the order, the smaller the typical wavelength to be taken into account.

Several points should be highlighted here:

- the amplitude of even orders is greater than for other harmonics. This is expected since they are successive harmonics of the M2 dominant group.
- Tiltmeters are able to record nonlinear waves up to 8 cycle/day. Note that neither loading gravity studies (Boy *et al.*, 2004) nor any other integrative geodetic method have been able to "see" these higher harmonic signals (although they are clearly seen in tide gauge records, of course). Hence tiltmeters turns out to be very sensitive tools to observe the deformation induced by the oceanic tides at the regional scale.

3.2. Tidal analysis

Earth tide analysis softwares are designed to estimate the transfer response of the Earth with respect to the astronomical gravity potential, usually providing the delta and gamma factors (Melchior, 1983). To search for higher tidal harmonics in the tiltmeter records, we therefore looked for tidal analysis tools which actually are standard within the sea-level community. We used the MAS software developed by Simon (2007) which implements a general method for analysing sea level heights. Pouvreau et al. (2006) compared MAS to the well-known and widely distributed T_TIDE software (Pawlowicz et al. 2002), and could not notice any significant difference from both sets of estimated tidal amplitudes at Brest. A drawback of the current T_TIDE release is, however, that it cannot analyse datasets longer than one-year, whereas MAS is successfully applied over periods even longer than a century.

Table 1 shows the main tidal constituents that we obtained from the ocean-like tidal harmonic analysis performed on the tiltmeter observations that were previously corrected from the Earth tides over the period 2004/03/09 to 2005/07/18. The units are expressed in nano-radians.

3.3 FES2004/NEA time modelling and sensitivity test distance

The modelling is performed by combining FES2004 global oceanic model (Lyard *et al*. 2004), and the refined NEA (North East Atlantic tidal solution) model in the close Atlantic and English Channel (Pairaud *et al.*, 2008).

We have plotted on figure 4 the modelled oceanic loading and the Earth Tide contribution, as well as the sum of these two signals and compared them with the observation. The chosen window permits to illustrate the best and the worst agreement. The largest discrepancies between modelled and observed oceanic loading occur for large tidal ranges. At the end of the window, during during small tidal ranges, the agreement is far better (the whole time-series is available on request). In general, the EW component is better modelled than the NS component. This may be linked to the coast orientation (EW) which is located 2km northwards of the observing site.

We do not know the origin of these discrepancies and their variations in time. However, we form the hypothesis that it could come from the interference arrangement between the main tidal M2 group and the overtones (nonlinear harmonics). We only took into account 8 waves in the diurnal and semi-diurnal bands here and none of the non-linear tides. A further check will require to model the whole M4 group and even upper modes.

Test distance

We tested the spatial sensitivity of the tiltmeters. We have chosen an adapted geographical windowing, as in Boy *et al.* (2003) to represent the different contribution of several areas. This method splits the oceanic contribution into parts according to an adequate division of the geographical areas. The relevance of these areas is linked to the specificity of the local and regional coast contouring. The choice of the zones is partially arbitrary and is only for discussion, but fundamentally also depends on the sensitivity of the method with respect to the distance, and hence on the power behaviour of the Green function: $1/r$ for gravity and $1/r^2$ for tilts.

Three zones were considered (see Figure 5):

- Z1 corresponds to the English Channel (based on NEA model)
- Z2 delimitate an intermediate zone (also based on NEA model)
- Z3 is for the other parts of the world (using FES2004)

Figure 5 also shows M2 wave amplitude. Figure 6 shows the cumulative contributions of each of these 3 zones for all the diurnal and semi-diurnal waves.

In the semi-diurnal band (N2, M2, S2 and K2), we observe the effect of the local magnification of the corresponding group periods. Large zooms are required to see the further contribution; the local signal is definitely dominant.

The diurnal waves (O1, P1, K1, Q1) form a second class of patterns. Though the local zone (English Channel) dominates the signals, the Atlantic and remote zones are almost of the same order of magnitude and none of the contribution could be neglected. This is due to the fact that the diurnal waves are not amplified by the Channel

Discussion and Conclusions

The sensitivity of the tilt method allows to observe the loading effect with a high signal/noise ratio. This implies that assuming a known mechanical response of the Earth, tiltmeters can be used to validate oceanographic models and nonlinear tides. Contrary to tide gauges whose spatial sensitivity is strictly local (and can be affected by the port configuration), the tilt offers an integrative measurement of the behaviour of the ocean with a regional spatial sensitivity.

They even could be more sensitive to coastal zones when tidal waves are magnified. This is the case for the M2 group; the wave amplitude is quickly decreasing when the distance to the coast increases, making the remote contribution really negligible.

The four main remaining issues are: 1) the difficulty to achieve a good accuracy in the calibration factor for this kind of tiltmeters, 2) the site effect, which is difficult to estimate in most cases, 3) the lack of atmospheric detailed data to correct from pressure within this short period band, and 4) the necessity to take into account a dynamical and coupled atmosphere-ocean modelling (see Boy *et al.*, this issue). However, these issues can be tackled in a near future. New experiments are carried on in Brittany near Ploemeur in France (Bour *et al.*, 2008) which could serve to improve our knowledge. Indeed, long-base hydrostatic tiltmeters have been set up in shallow galleries. They have been recording for a few months. Both calibration uncertainties and site effects will be easier to solve there for that kind of instruments. In parallel, atmospheric sampling rates and coupled modelling with the oceans are continuously improving.

Due to its features and assuming further improvements, tilt could become a systematic tool to test oceanic models as far as non linear high harmonics are concerned. Neither gravity nor GPS techniques are able to see M4, M6, M8 and M10 waves with such a signal/noise ratio as the one reached by tiltmeters today.

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Figure captions:

Figure1 : Site location and installation of a Blum Pendulum in the “Souterrain du Roule” at Cherbourg

Figure2 : EW and NS raw and band-pass filtered tilt records at Cherbourg

Figure 3 : Fourier analysis (periodogramms) of the tilt records reveal a high signal/noise ratio of 100 (40 dB) at 2 cycle/day. It detect peaks till the 1/10 diurnal cycle.

Figure 4: on the bottom part, Earth tide and loading models are shown separately, while there are summed in the top part of the figure. In both cases, the observation is also plotted and shows a greater amplitude than the model. The misfit could be due to non-linear tides that are not included in this computation.

Figure5 : The computation is performed by distinguishing three exclusive zones: this enables to study the influence of close, intermediate and distant oceanic loading effects. Zone 1: from -5° to 1.5° in long and 48.5° to 51.25° in lat; Zone 2: from -20° to 14° in long and 30° to 61° in lat (excluding Z1); Zone 3: global excluding Z1 and Z2. In Z1 and Z2 the North-East Atlantic (NEA) tidal solution (Pairaud et al., 2008) is used, while Z3 is computed by using FES2004 model (Lyard et.al., 2006).

Figure 6: Cumulative contribution of the 3 different zones for all diurnal and semi-diurnal waves.

Table 1 : Results from the ocean-like tidal harmonic analysis applied to the tiltmeter observations (2004/03/09-2005/07/18) previously corrected for the Earth tides.

Tidal constituent	ALPHABETICAL DOODSON NR.	Amplitude East-West (in nano-radians)	Amplitude North-South (in nano-radians)
M2	BZZZZZZ	435	404
S2	BBXZZZZ	149	141
N2	BYZAZZZ	85	82
K2	BBZZZZZ	41	40
K1	AAZZZZA	34	23
O1	AYZZZZY	19	6
P1	AAXZZZY	11	6
Q1	AXZAZZY	1	10
M4	DZZZZZZ	12	32
MS4	DBXZZZZ	8	20
MN4	DYZAZZZ	4	10
M6	FZZZZZZ	3	7
2MS6	FBXZZZZ	3	8
2MN6	FYZAZZZ	2	5
5MS8	HXBZZZZ	1	6

Figure 1

Canal de Bristol
(Londres)
London
(Bruxelles
Manche
Guernsey
Jersey
Saint Helier
Paris
208 km
Google

Figure 2 :

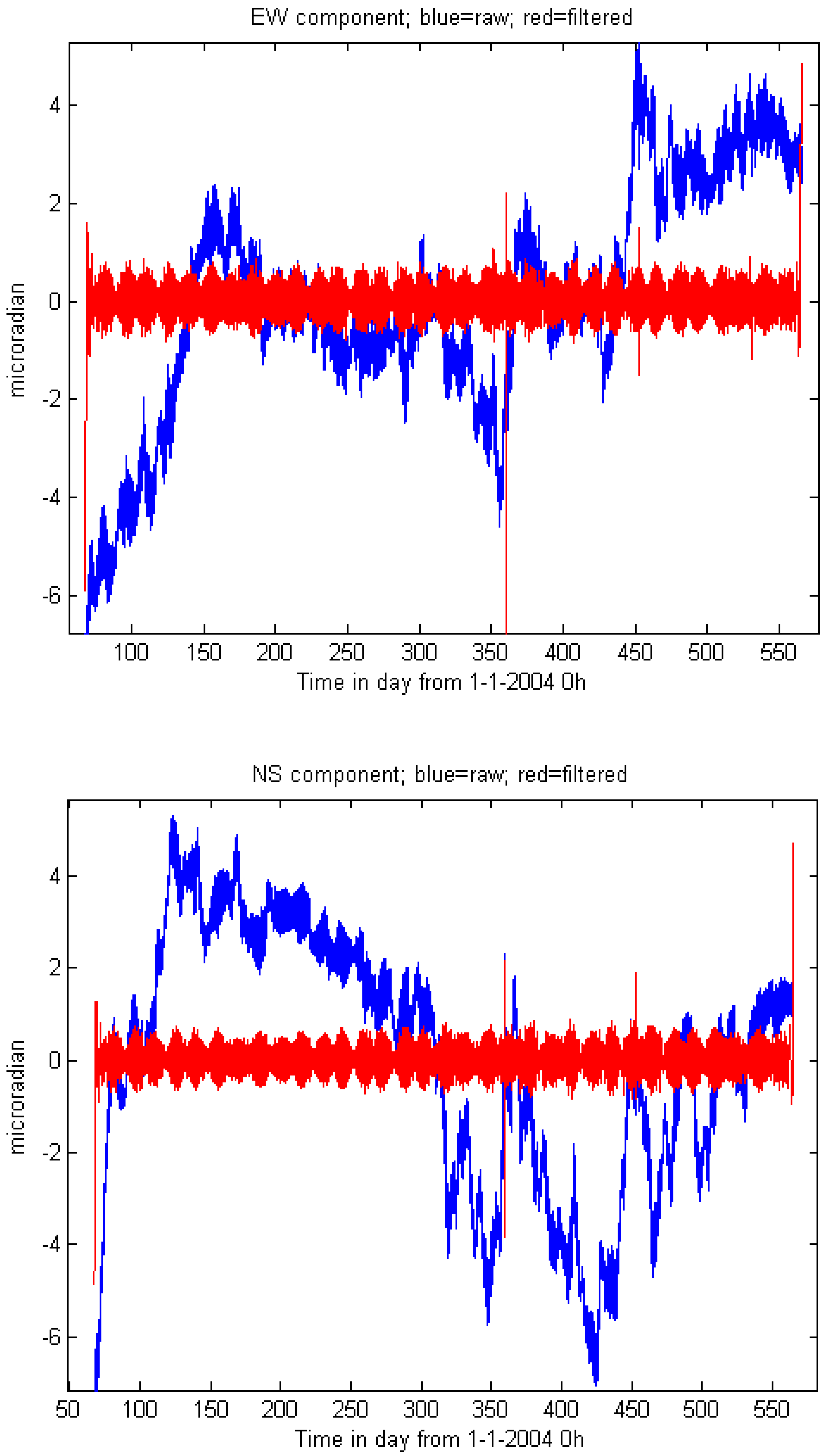

EW component; blue=raw; red=filtered
microradian
4
2
0
-2
-4
-6
100
150
200
250
300
350
400
450
500
550
Time in day from 1-1-2004 0h
NS component; blue=raw; red=filtered
microradian
4
2
0
-2
-4
-6
50
100
150
200
250
300
350
400
450
500
550
Time in day from 1-1-2004 0h

Figure 3

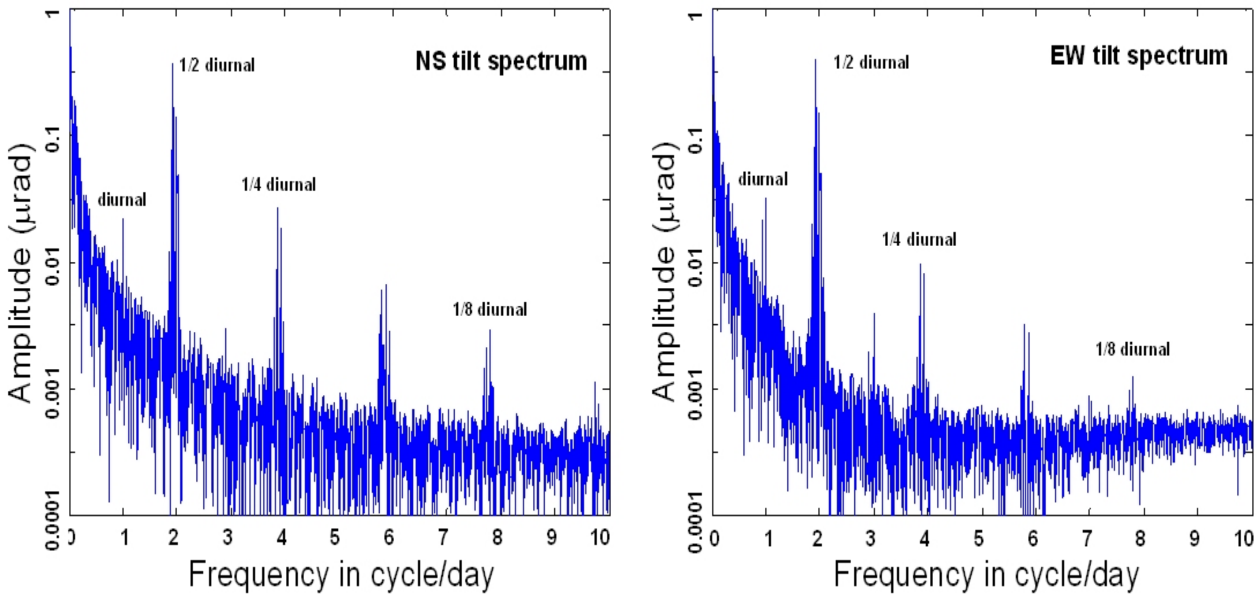

NS tilt spectrum
1/2 diurnal
diurnal
1/4 diurnal
1/8 diurnal
Amplitude (µrad)
Frequency in cycle/day
EW tilt spectrum
1/2 diurnal
diurnal
1/4 diurnal
1/8 diurnal
Amplitude (µrad)
Frequency in cycle/day

Figure 4

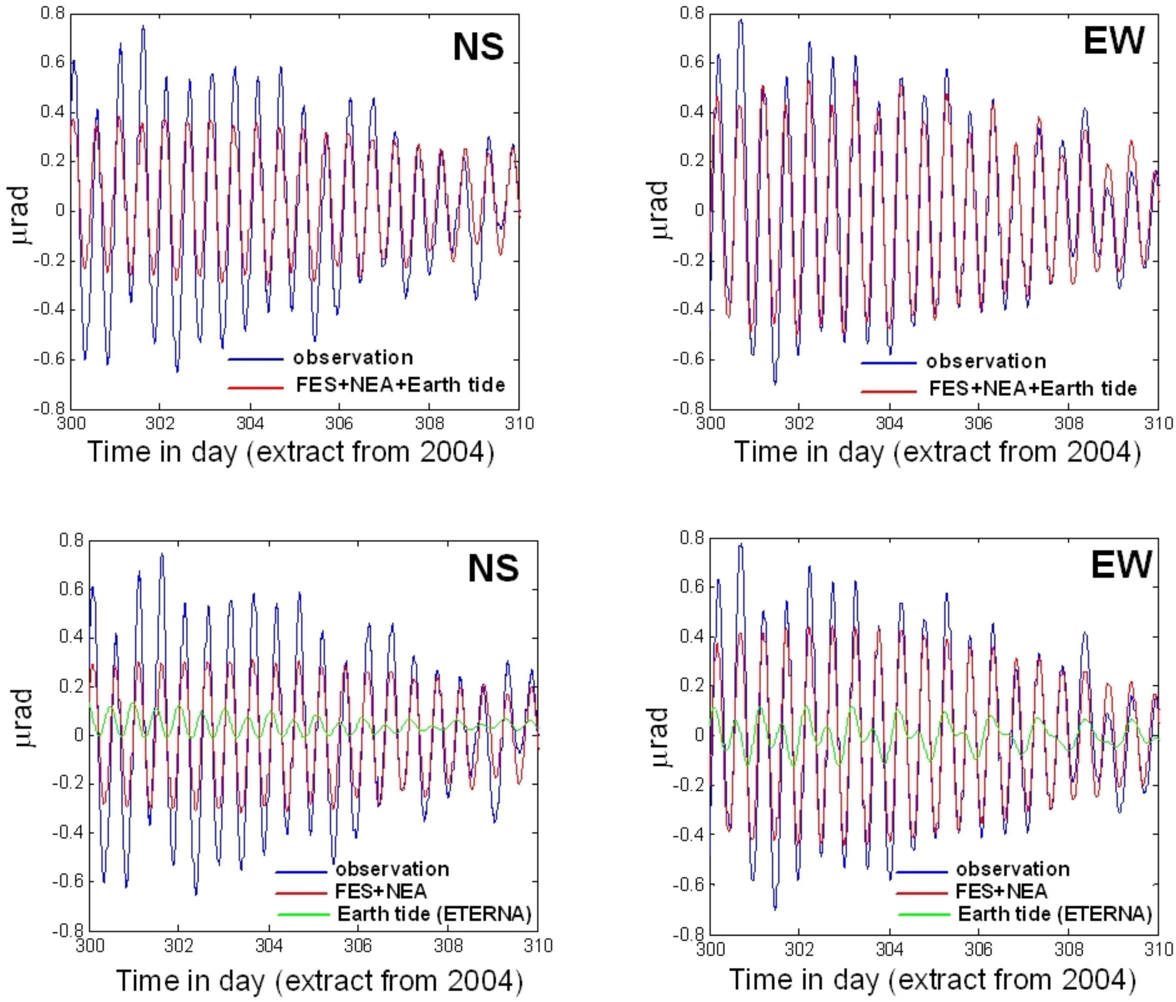
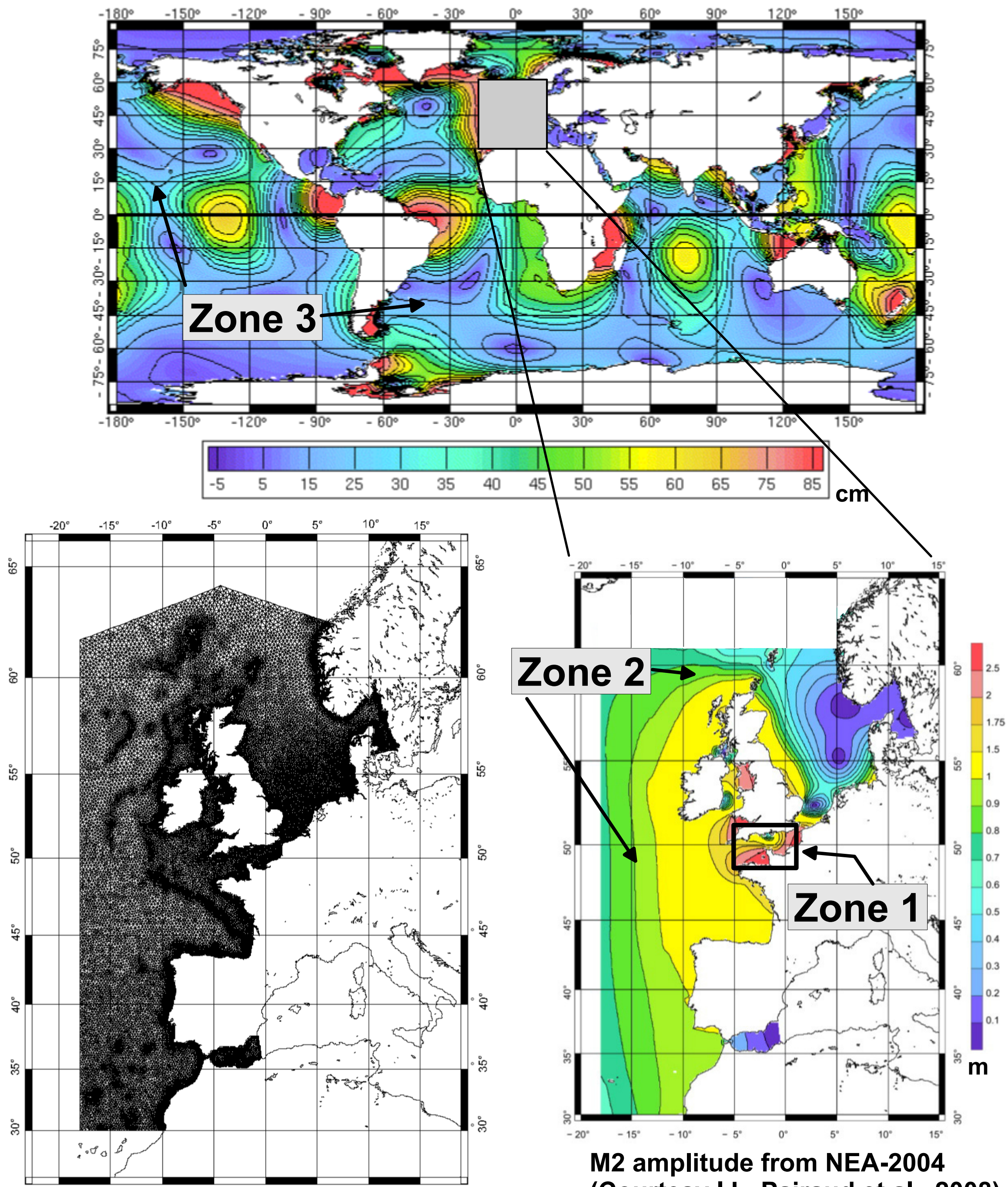

NS
μrad
observation
FES+NEA+Earth tide
Time in day (extract from 2004)
EW
μrad
observation
FES+NEA+Earth tide
Time in day (extract from 2004)
NS
μrad
observation
FES+NEA
Earth tide (ETERNA)
Time in day (extract from 2004)
EW
μrad
observation
FES+NEA
Earth tide (ETERNA)
Time in day (extract from 2004)

Figure 5

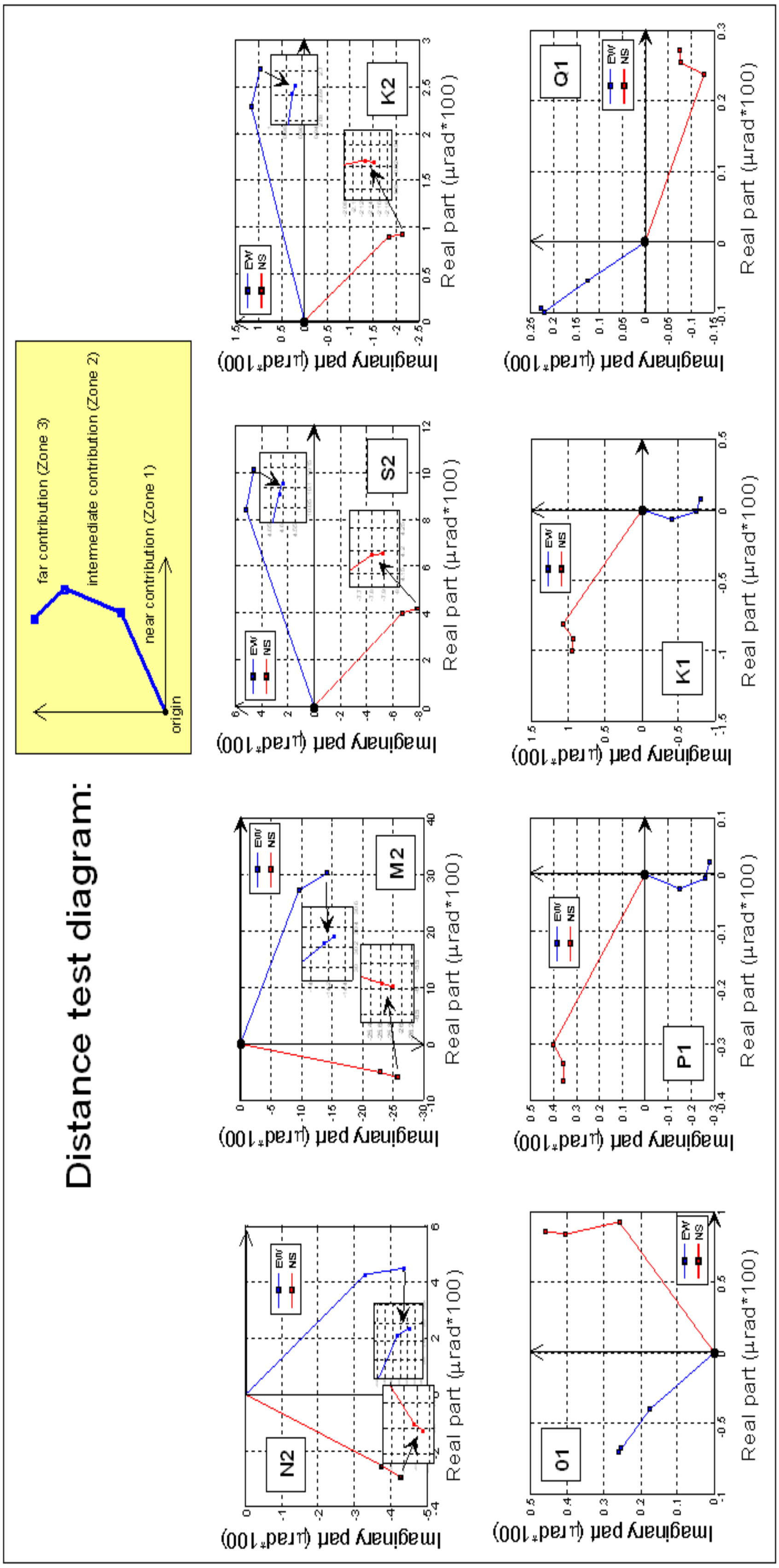
FES2004 model, M2 amplitude (F. Lyard et al., 2006)



M2 amplitude from NEA-2004
(Courtesy I.L. Pairaud et al., 2008)

Unstructured grid T-UGAm model used to compute NEA-2004 tidal solution.
(Courtesy I.L. Pairaud et al., 2008)

Figure 6



Distance test diagram:
far contribution (Zone 3)
intermediate contribution (Zone 2)
near contribution (Zone 1)
origin
N2
M2
S2
K2
O1
P1
K1
Q1
EW
NS
Real part (µrad*100)
Imaginary part (µrad*100)